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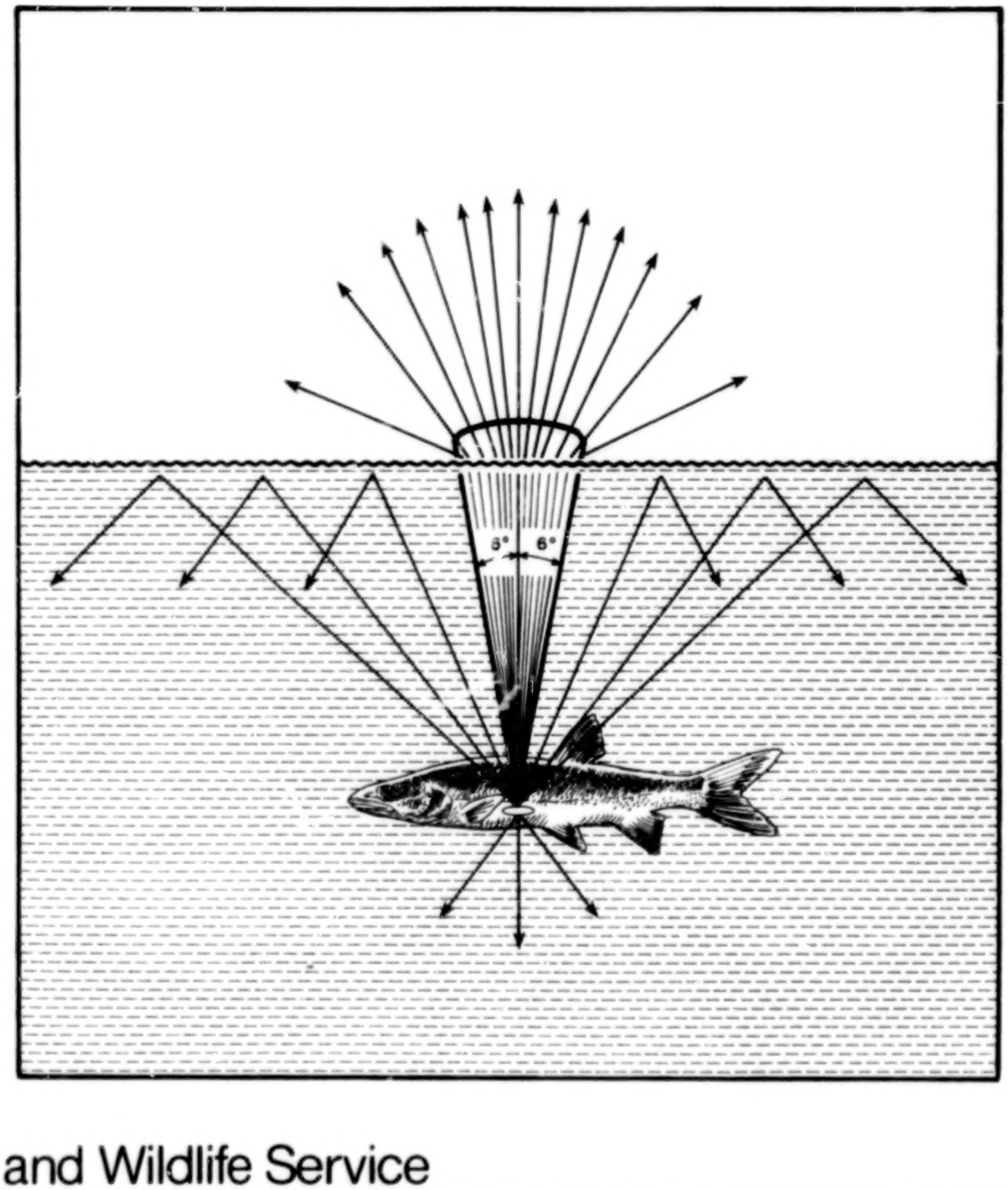
FISH RADIOTELEMETRY: THEORY AND APPLICATION FOR HIGH CONDUCTIVITY RIVERS



Fish and Wildlife Service
U.S. Department of the Interior

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- To gather, analyze, and present information that will aid decisionmakers in the identification and resolution of problems associated with major changes in land and water use.
- To provide better ecological information and evaluation for Department of the Interior development programs, such as those relating to energy development.

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FISH RADIOTELEMETRY:
THEORY AND APPLICATION FOR HIGH CONDUCTIVITY RIVERS

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EXECUTIVE SUMMARY

Theoretical and applied information about radiotelemetry related to rivers with high conductivity (over 600 µmho) is presented in this report. Material is divided into two main sections, Theoretical Considerations and Radiotelemetry Field Studies.

Theoretical information is presented in a simplified form for investigators new to the radiotelemetry field. Radiotelemetry and ultrasonics are compared as methods for obtaining information about fish movements in turbulent, turbid river systems. Radiotelemetry is the most suitable method for turbulent rivers. The propagation of radiowaves and the use of radio transmitting antennas in water are discussed from the viewpoint of improving reception efficiency. The components of radio receiving systems are analyzed and related to efficiency of operation for field workers.

Results from field studies conducted in 1980 by the U.S. Fish and Wildlife Service were used to evaluate the reception of radio transmissions from fish under natural conditions. Some data on range vs. depth and conductivity with different antennas and radio transmitters are presented. Field workers who use radiotelemetry are cautioned to carefully consider equipment limitations and physiochemical features of water before studies are inititated.

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INTRODUCTION

The U.S. Fish and Wildlife Service (FWS) is evaluating the status of four endemic fishes of the Colorado River system. Three of these fish are classified as endangered under the Endangered Species Act of 1973 (P.L. 93-205): the Colorado squawfish (*Ptychocheilus lucius*), the humpback chub (*Gila cypha*); and the bonytail chub (*Gila elegans*). The fourth fish, the razorback sucker (*Xyrauchen texanus*), is proposed as threatened. Because of the difficulty of working in the remote upper Colorado River system with its whitewater sections, the FWS became interested in the feasibility of using radiotelemetry to learn more about the life histories of these fishes. The Colorado squawfish was selected for initial work because of its large size and availability in flat water sections of the Green River.

In 1978, the FWS employed a contractor to study the spawning requirements of Colorado squawfish in the Green River of Utah. Results of this preliminary study were reported by Holden and Selby (1978) and are discussed in this report. The FWS also sponsored a study to investigate the feasibility of radio tracking Colorado squawfish in the Green River, Utah (Sinning 1979). Sinning's report included theoretical information on radiotelemetry, an evaluation of the previous radiotelemetric study in the Green River, and synthesized information from other studies. Sinning concluded that radiotelemetry results would be marginal in the Green River because high conductivity impedes radiosignal transmissions in water. Further feasibility studies were recommended.

The FWS began a radiotelemetry study on the Green River in March 1980. This study was initiated because of an urgent need for data on habitat preferences of Colorado squawfish. These data were needed for incorporation into recovery plans required by the FWS for all endangered species and the information base used for evaluating proposed upper Colorado River Basin development projects.

Theoretical information assembled by Sinning (1979) and data obtained during the FWS study (Tyus et al. 1981) are included in this report. Material prepared by Sinning (1979) has been rewritten, simplified, and oriented toward the needs of other investigators. Basic radioreception information obtained by the FWS is presented in an effort to relate theoretical considerations to field applications. Practical information on the effectiveness of radiotelemetry has significance for other investigators working in rivers of high conductivity.

THEORETICAL CONSIDERATIONS

TYPES OF TELEMETRY

Radiotelemetry has been used to monitor movements and other behavior of terrestrial animals for many years. Earlier workers did not use radiotelemetry for studying fish movement because it was believed that radiotransmission through water would be too poor to be effective. Most of this early work involved use of ultrasonics (Stasko and Pincock 1977). The suitability of using both techniques is evaluated below.

Ultrasonic Telemetry

Ultrasonic transmissions of high frequency sound waves have been successful in many aquatic systems. Frequencies employed are usually between 30 and 200 kHz, which are not audible to the human ear. Ultrasonics have an advantage over radiotransmissions for tracking fish under certain conditions. For example, ultrasonic transmission range is not greatly affected by dissolved solids. Also, a hydrophone (receiving collector) is generally more directional than a conveniently sized radio antenna due to the shorter acoustic wavelengths and the slower sound velocity. The slower velocity allows the pulse interval to be used in computing the distance travelled from the transmitter to the receiver (Stasko and Pincock 1977).

There are, however, several disadvantages of ultrasonic tracking. For example, the detection of ultrasonic signals require that the receiving hydrophone be immersed in water. This makes tracking difficult with ice cover and also eliminates the use of aircraft. Aircraft use may be essential in a large river system, especially if numerous tagged fish are being tracked.

Ultrasonic telemetry is markedly influenced by water temperature, turbulence, and sediment load. Temperature affects the velocity of ultrasonic emmissions and a thermal discontinuity may reflect ultrasonic energy away from the hydrophone (Sinning 1979). Entrained air from waves, boat propellers, and turbines in dams may cause enough noise to mask ultrasonic reception, as does the movement of bottom sediments caused by stream currents. The only known use of ultrasonics in the Green River was marginally successful due to water turbulence and transmission blockage by rocks and vegetation (McAda and Wydowski 1980).

Radiotelemetry

Radiotelemetry involves the generation (by a transmitter) and propagation of radio waves (electromagnetic radiation) through water. The transmitted energy must then cross the air-water interface and be received by an antenna operating in air. Although radio frequencies of 10 kHz to 50 MHz have been experimented with in water, frequencies between 40 and 160 MHz are usually used.

The propagation of radio waves through any medium, in this case water, is inversely proportional to the frequency. Thus, radio waves of high frequency travel a given distance with a greater loss of power than an emission of lower frequency. The nature of the change in propagation with frequency is approximately logarithmic (Lonsdale 1967; Lonsdale and Baxter 1968). Radio signals are attenuated (diluted) more rapidly in water than air, and the amount of attenuation is inversely proportional to the conductivity of the water (Weeks et al. 1977). For this reason, a considerable loss of signal strength is expected when radio waves are propogated through fresh water of high conductivity. Radio transmission in salt water is virtually impossible.

The behavior of radio energy at the air-water interface (Fig. 1) is an important consideration for radiotelemetry. Energy contacting the interface is reflected unless the angle of incidence is less than 6° (Weeks et al. 1977). Radiation of the energy that passes this interface produces a signal with the apparent signal source being a circle on the surface of the water (Priede 1980).

The preceding explanation does not account for the reflection of radio energy from the water surface to the bottom and back through the surface, or radiation from anything other than a smooth surface. However, these additional effects result in a signal being emitted from the surface in a pattern different from that predicted by theory. Sinning (1979) noted that the U.S. Navy, which experimented with subsurface radio emissions for over 30 years, uses a surface antenna for submarines. This is evidence of the difficulties with long distance underwater radio transmissions yet to be solved.

Factors, other than the propagation of radio transmissions through water, must also be considered. The most obvious one is the strength of the emitted radio signal. The range of a signal is directly proportional to the power of the transmitter. Power radiated by the transmitter is a function of the efficiency of both the transmitter and the transmitting antennas. These efficiencies are typically 65 to 70% for underwater applications when the radiated transmitter output is contrasted with battery power entering the transmitter (Sinning 1979).

Antenna efficiencies (Terman 1955) can be lower (less than 1% to 25%) than transmitter efficiencies. When losses of efficiencies for transmitters and antennas are combined, antenna efficiency may range from less than 1% to 18% of the battery power.

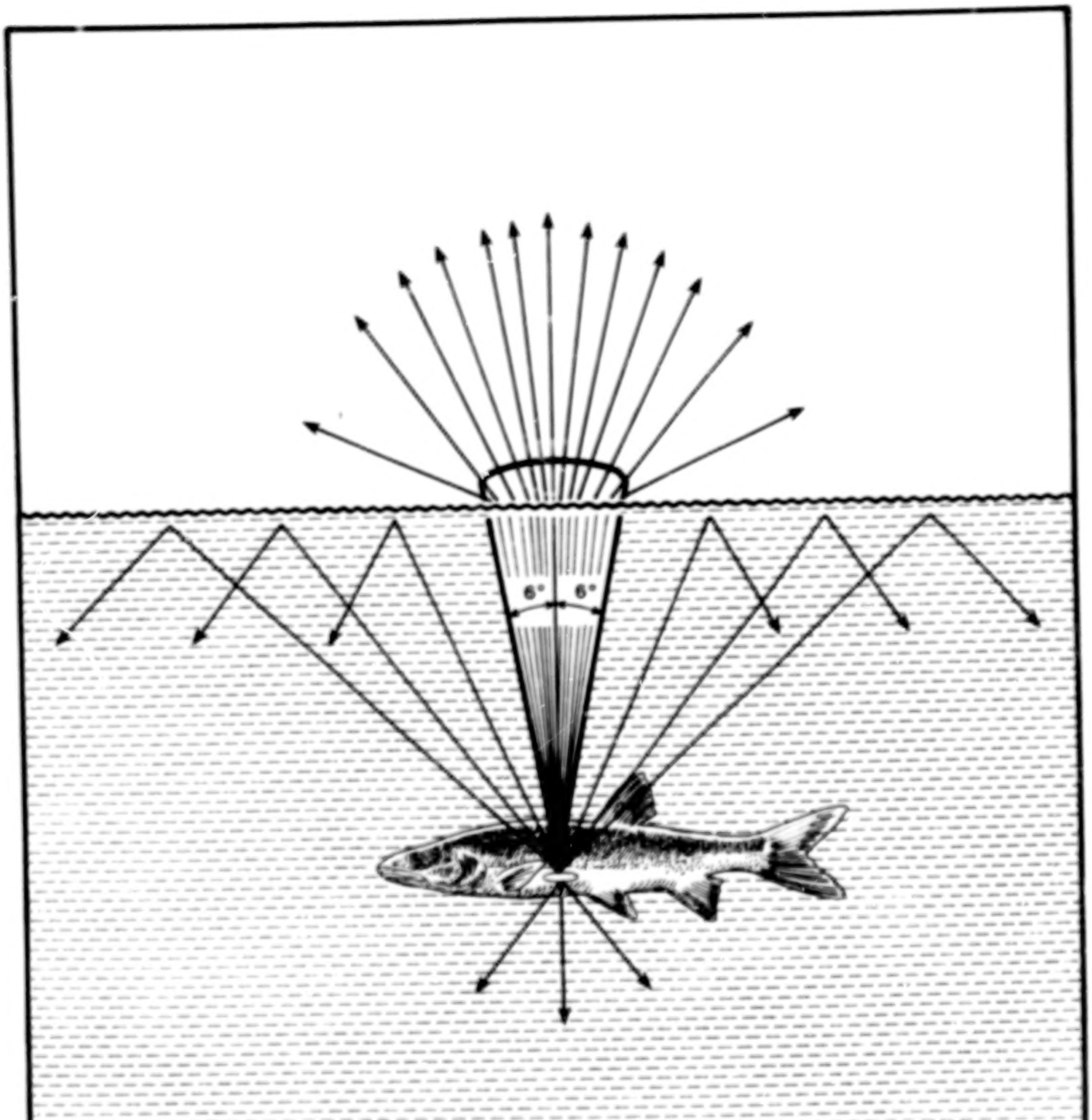

Figure 1. Radio signals from a transmitter, passing through the air-water interface.

Only a small portion of this radiated power actually crosses the air-water interface and is available to the receiving system. However, if any "significant" energy breaks through the interface, radio reception can occur at long ranges because of the rapid propagation of radio waves in air (Stasko and Pincock 1977).

The type and size of battery used with radiotransmitters is an important consideration from the standpoint of size, weight, range, and life. For a given application, battery weight and size is directly proportional to range (power output) and the transmission life. Fish transmitters can be designed to operate for hours to years with a given battery, but the range decreases as transmitter life increases. Although range can be increased by using a larger battery, the weight and size increase may not be acceptable. The theoretical longevity of a battery may be obtained by dividing the current demand (drain) of the transmitter (milliamps) into the battery rated capacity (milliamp days). Transmission lives and sizes of some batteries are provided in Tables 1 and 2.

In review, radiotelemetry is a better tool for monitoring the movement of fishes in certain aquatic environments, especially those in which use of ultrasonics may be infeasible. Ultrasonics has great value in quiet water and may be better for deep lakes, but radiotelemetry seems to be better for monitoring fish movement in rapidly flowing rivers. As stated by Priede (1980:110): "Radio signals are not affected by air bubbles, water turbidity, or obstructions... the way that sonic signals are." Also, ultrasonic signals are not suitable for aerial reception (e.g., by airplane) because the hydrophone must be immersed in water to receive the ultrasonic signals. Although transmission through the air-water interface greatly reduces the apparent signal strength of radio waves, reception in air is possible and the signal strength is adequate for most applications.

Radiotelemetry in high conductivity waters is marginal (Sinning 1979), and efforts must be taken to maximize the strength of the radio signal in the field. Increases in received field signal strength from a transmitter to a receiving radio is dependent on the efficiency of transmitting and receiving antennas. Available transmitter designs represent the state-of-the-art technology, and loss of efficiency between transmitting and receiving antennas is largely dependent on fish behavior and water conductivity.

RADIO TRANSMITTING ANTENNAS

Only a few types of transmitting antennas are suitable for monitoring fish movements. The two main types are straight whip and tuned loop. Whip antennas are generally small and omnidirectional. Although a whip antenna can be compressed in length by shortening it from 0.5 to 0.25 wavelength, or by coiling part of it, a loss in efficiency occurs. A decrease of the diameter of an antenna also lessons efficiency. The required length of the whip antenna is dependent on the wavelength, and reducing the wavelength by raising the frequency will allow greater efficiency for a given antenna size. Unfortunately, a frequency increase lessens the wave propagation through water;

Table 1. Specification of mercury (Hg) batteries. (Courtesy AVM Instrument Co. 1979)

Battery	Weight (g)	Diameter (cm)	Height (cm)	Rated capacity (ma-days)	Theoretical life at various transmitter current drains		
					.07 ma	.16 ma	.28 ma
Hg-212	.3	0.5	0.4	0.9	13 days		
Hg-312	.6	0.7	0.4	1.8	1 mo.		
Hg-575	1.2	1.2	0.4	4.0	2 mo.		
Hg-675	2.4	1.2	0.5	8.0	4 mo.		
Hg-630	4.6	1.5	0.6	14.0	6½ mo.		
Hg-640	7.3	1.6	1.1	20.0	9½ mo.		
Hg-828	12.4	2.3	0.7	40.0	1½ yr.	8 mo.	4½ mo.
Hg-1	13.2	1.6	1.7	40.0	1½ yr.	8 mo.	4½ mo.
Hg-601	22.0	1.6	2.9	75.0		15½ mo.	8½ mo.
Hg-12	40.0	1.5	5.0	140.00		2½ yrs.	16½ mo.

Table 2. Specification of lithium (Li) batteries. (Courtesy AVM Instrument Co. 1979)

Battery	Weight (g)	Diameter (cm)	Height (cm)	Rated capacity (ma-days)	Theoretical life at various transmitter current drains		
					.07 ma	.16 ma	.28 ma
Li 1/2A	9.5	1.6	2.1	31	6½ mo.	3 3/4 mo.	3 mo.
Li 2/3A	13.5	1.6	3.2	50	10½ mo.	6 mo.	4 3/4 mo.
2 Li 2/3A's in parallel	27			100	21 mo.	1 yr.	9½ mo.
Li C	47	2.5	4.7	208	3 ½ yr.	2 yrs.	1½ yrs.
2 Li C's in parallel	94			416	7 yrs.	4 yrs.	3¼ yrs.

thus, the gain in efficiency of antenna operation is less at higher frequencies. The precise relationship of these two contradictory effects is unknown (Sinning 1979); however, the magnitude of effect probably varies with environmental conditions.

The use of water rather than air as a medium for radiotransmission requires shorter antennas. The usual antenna length is 0.25 wavelength. Wavelength size depends on the velocity of the generated radiowave, which decreases with increasing dielectric constant of the medium. Because the dielectric constant for water is about 80, the length of the transmitting antenna may be reduced from that required for air (dielectric constant about 1.0) (Weeks et al. 1977). The velocity of radiowaves in water is about 0.11 that of air; therefore, 0.25 wavelength antennas of commonly used frequencies of 15 to 50 MHz may be reduced from 1.5 to 0.5 m in air and from 0.17 to 0.06 m in water. These lengths (0.17 to 0.06 m) are acceptable sizes for transmitters used in most fish studies.

It is theoretically possible to increase the efficiency of a transmitting whip antenna to increase the strength of the received signal. Because the resistance of the media (water) to radio transmission cannot be controlled by the investigator, the only other variable relative to the antenna is antenna length. An investigator might gain efficiency by making a whip antenna longer than 0.25 wavelength and as straight as possible. Unfortunately, this increase in length may not be desirable for transmitting antennas used in fish work, especially if the transmitter is to be used with smaller fish species.

The use of a loop or coiled transmitting antenna is highly desirable for modules surgically implanted in fish because of the necessity for compactness. It may be possible to increase the radiation resistance (antenna efficiency) of some types of coiled antennas by increasing the length of the coil. However, for a "tuned" inductor type, the coil is part of a circuit and resonates at a certain mode. The tuned inductor type antenna, therefore, cannot be made more efficient simply by increasing the length (Kolz, pers. comm.). A more detailed discussion of loop antennas is beyond the scope of this report; however, these antennas have considerable application in fish research.

RADIO RECEIVING SYSTEMS

The receiving system for radiotelemetry consists of an antenna, a receiver, and the interconnecting transmission line (Fig. 2). The size of an antenna in air must be nine times larger than in water. Size considerations are very important if an aircraft is to be used for tracking because of wind resistance. Small antenna size is also desirable if tracking is done from shore or a small boat. Receiving antennas work best when elevated; however, there can be constraints on heights due to field conditions.

Transmitting antennas must radiate radio signals in all directions. Receiving antennas should have a capability for receiving from all directions as well as functioning unidirectionally. The only practical approach to this problem with existing technology is to employ two separate antennas. For fish

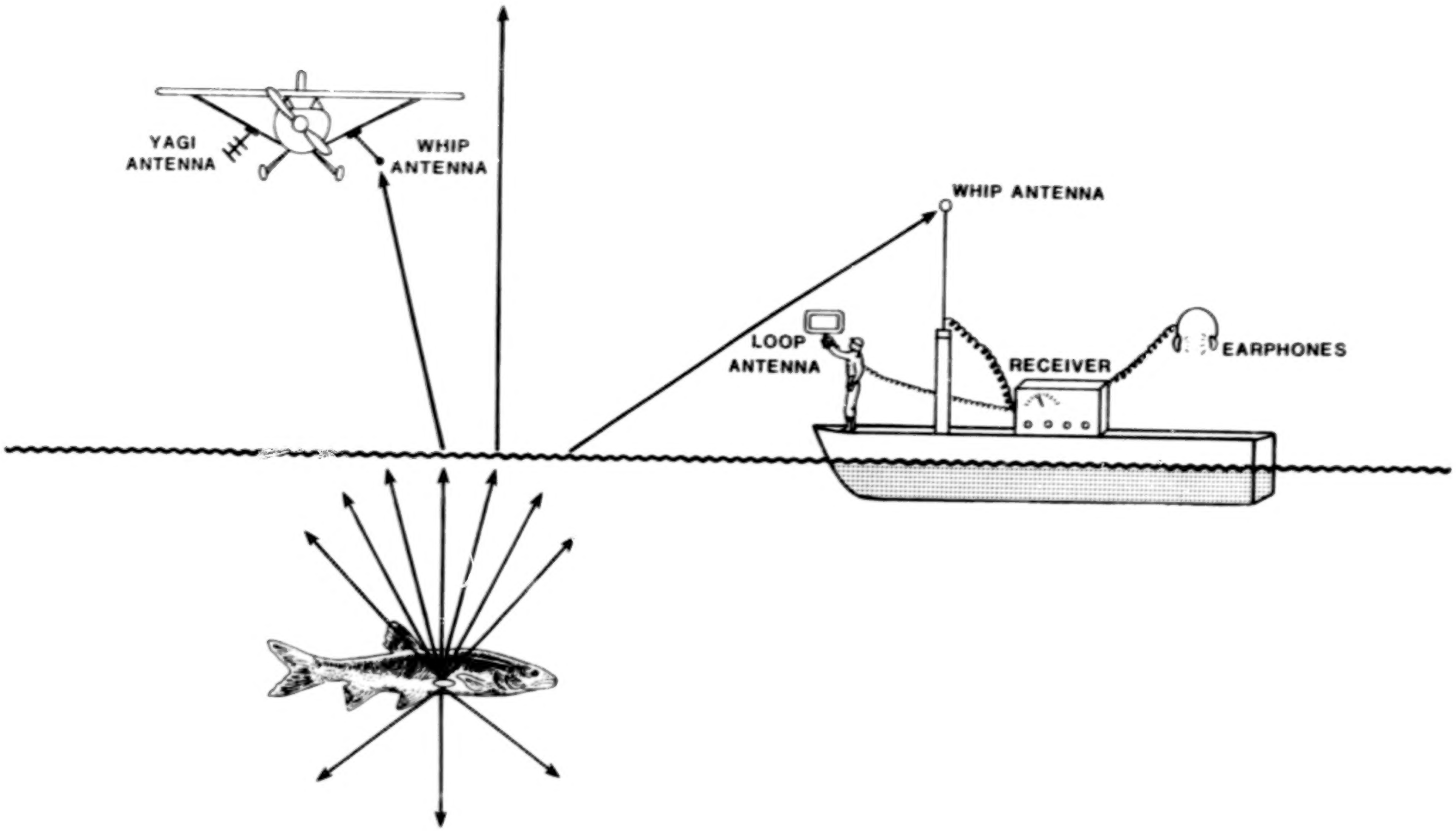

Figure 2. Radio signals from an implanted fish to receiving systems illustrating different types of antennas.

work, the omnidirectional straight (or whip) antenna can be used to receive signals from all directions. For monodirectional tracking, either a loop or Yagi antenna may be used. The loop antenna resembles a hoop on a stick, while the Yagi type consists of several short cross pieces mounted on a vertical pole. The short sections (elements) are mounted perpendicular to the vertical plane and attached at their midpoints (Fig. 2).

The 0.25 wavelength antenna at 50 MHz for a simple whip antenna is about 1.5 m. The whip antenna usually rests on some object on the ground plane. A ground reference plane placed perpendicular to the whip antenna aids in efficiency. The whip antenna is more sensitive than a loop, but less sensitive than a Yagi. Its advantages are simplicity of design, low cost, and ease of mounting. This antenna has the least air resistance and, for this reason, may be preferred for aircraft use. The convenience of a whip antenna may make it more desirable than a Yagi, and many investigators believe the loss in efficiency may not be significant (Knight, pers. comm.). In addition, the Yagi antenna may pick up significant noise in some locations and mask the transmitter signal, especially if antennas are stacked (i.e., if more than one antenna is mounted on a single pole) (Ringe, pers. comm.).

Loop and Yagi antennas are used to locate a signal source by rotating the antenna until the maximum (or minimum) signal strength is detected. For the Yagi antenna, the gain (efficiency) increases with an increasing number of elements in the antenna although the rate of increase becomes less with each element that is added. Each element of the 0.5 wavelength antenna is approximately 3 m long at 50 MHz and about 1 m long at 150 MHz. These elements are mounted on a boom that ranges in length from about 1.5 m for a 2-element Yagi antenna to nearly 4 m for a 5-element Yagi antenna at 50 MHz. The antenna should be at least 0.5 wavelength from the nearest large object in order to be highly directional and effective in radio signals (gain). A 50 MHz antenna must be mounted at least 3 m above the ground because ground reference may interfere with performance. Yagi antennas are most effective when used from a fixed location because of the constraints discussed above and the large size of the antenna. However, Yagi antennas have been used successfully from a 4 to 5 m boom on small aluminum boats (Ringe, pers. comm.).

The loop antenna does not have as much gain or directivity as a Yagi antenna, but it can be made much smaller and more rugged and is less sensitive to interference from objects in its proximity. Loop and Yagi antennas are bidirectional and require readings from two different locations so that triangulation can be used to locate the signal source. A simple bidirectional loop antenna for 50 MHz is about 1 m in diameter. Smaller diameters can be used but some loss of sensitivity is to be expected.

After the antenna has received the radio signal, the signal is relayed through coaxial cable to the receiver where it is converted to an audio and/or visual signal. Coaxial cables have unavoidable efficiency losses due to their construction. These losses can be minimized by the proper choice of cable and by keeping cable lengths short. Connectors also cause a loss of efficiency. Some investigators have used coaxial splitters to separate the signal from one coaxial cable to two cables. This method allows one antenna to be shared by both a search and a pinpointing type receiver. Since this can result in a loss of received signal strength, it should be avoided. Other investigators have used signal strength boosters between the antenna and receiver. However, care must be taken so that the noise level is not boosted enough to interfere with signal reception (Ringe, pers. comm.).

Losses associated with the transfer of signals between the antenna and the receiver are usually small but they can significantly affect field results. For example, water, dirt, or corrosion on the conductors can diminish the signal strength. These effects must be recognized and avoided by careful upkeep of equipment, especially in waters of high conductivity where signal propagation is suboptimal.

The radio signal is converted in the receiver to an audio, visual, or other type of display useful to monitoring personnel. Receiver design involves many considerations and currently approaches theoretical limits for factors such as sensitivity (primarily limited by thermoelectric noise generated within the receiver) and selectivity (ability to differentiate the desired signal from other signals).

There are two principal types of receivers: 1) the search (or scan) receiver which will pick up a variety of signals (ideally from any transmitt[illegible] in use); and 2) the tracking (or pinpointing) receiver which is used to locate and identify individual transmitters. Any major field study should involve use of receivers with search and track capabilities, especially if several transmitters are used. A search model can prevent loss of a fish if temperature changes or other factors cause a transmitter to emit a different frequency. The scan receiver, however, cannot be tuned as precisely as a pinpoint receiver and may not have as great a range in terms of strength of signal received or distance.

RADIOTELEMETRY FIELD STUDIES

BACKGROUND

Sinning (1979) compiled information from several radiotelemetry fish tracking studies done in waters of conductivities of 600 µmho's or less (Table 3). Some studies were not referenced in Table 3 because results were similar to those referenced or the publications reporting on the study were not readily available. At least partial success was reported for all of the studies referenced in Table 3. The highest reported water conductivity was 600 µmho, with a useable signal depth of about 2 m. No signal could be detected at 6 m in water of this conductivity. Most of the transmitters used in the studies were homemade with widely variable design characteristics. Receivers varied from sophisticated communications equipment to converted inexpensive transistor radios. For most of the studies, receiving antenna types and specifications were not reported. The type of receiving antenna can make a major difference in the range at which transmissions can be received.

Table 3 also presents some conditions affecting reception at different ranges. Conditions which could affect range but are not listed include antenna type, water surface character (e.g., wave action), antenna height, transmitter output power, transmitter antenna type, receiving antenna gain, transmission line losses, receiver noise, and presence and strength of interfering signals.

Results of radiotelemetry studies listed in Table 3 were evaluated by Sinning (1979) and analyzed by linear regression. Results of the regression analysis were essentially inconclusive, probably due to variation in the equipment used in the studies. However, when data from Larimore et al. (1975) were analyzed, the regression of the log of the depth versus the range was significant at $P \leq 0.5$ ($r = 0.998$, $n = 3$) for 600 µmho conductivity. This simply implies that the range decreases as the depth increases. A manual published by the AVM Instrument company (1979) includes ranges for their 49 to 50 MHz fish modules at 600 µmho conductivity, which seem to correlate with range and depth relationships discussed by Sinning (1979).

Although attempts have been made to predict the range of radiotelemetry at given depths and conductivity values, a predictive model for practical application has not been developed. It is uncertain if a model could be developed for practical use since environmental variables and different radio transmitting and receiving systems introduce large error terms. Even if predictive models could be developed, they may have limited utility because researchers often have to experiment with equipment to attain satisfactory results in different environments.

Table 3. Summary of radio tagging studies (after Sinning 1979).

Location	Frequency (MHz)	Water conductivity (μmho)	Ranges obtained (km)	Depth (m)	Tag life (days)	Equipment used and weight (gm)	Attachment method
Lake Michigan	not given	250-350	3 1	2.5 7	24	H.B.[a]; 12.5	external (internal sensor)
mid-Columbia R.	53	250 estimated	1.5-3.0 0.3-0.8	0 15	approx. 360	H.B.[a]; various sizes and weights 15 to 70	external
Penobscot R., Maine	49	46	9.75 10.9 10.05 6.2	0.1 1 2 3	7-136	Dav-tron 10-16	gastric
Nogies Creek, Ontario	50	150 estimated	1.5 0.3	0.5 5	>350	AVM; 14 (air)	internal
Savannah, R., Georgia & S. Carolina	not given	not given	not given	not given	not given	AVM; 20 (air) 10 (water)	internal
Lake Bemidjc, Minnesota	53	300 estimated	0.006-0.016 1.2-1.6	5 <2.5	not given	H.B.[a]; 30 (air) 16 (water)	external
Penobscot R., Maine; Connecticut R., Massachusetts; Aquariums	30	46 unknown	0.18-0.55	<45	6-12	H.B.[a] and Erie Technological Products - Tags AVM & Dav-tron - Receivers 3 (internal tags) 3.5 (external tags)	internal and external

Table 3. Concluded.

Location	Frequency (MHz)	Water conductivity (μmho)	Ranges obtained (km)	Depth (m)	Tag life (days)	Equipment used and weight (gm)	Attachment method
Mary Lake, Minnesota	53	150 estimated	0.8-1.2	3	60-90	H.B.[a]; 14-15	external
Penobscot River, Maine	30	100 estimated	0.5-1.5	45	7	H.B.[a]	gastric
Conn River, Mass		1.4 gm/l salinity	0.1	2			
Illinois (Cooling Lake)	50	450-600	0.9 0.5 0	1 2 6	400-600	H.B.[a]; 10	internal
Lake Michigan	not given	250-350	4.6 1.5	4 10-15	7	not specified	external
Lake Mendota, Wisconsin	53	450 260	3.5 6.0	1 1	2	H.B.[a]; 25 (water)	not given
Northern Minn. (Lake)	53	100-300 estimated	1-3	not given	70-80	H.B.[a]; 26 (water)	external
Parvin and Redfeather Lakes, Colorado	100-130	100 estimated	0.045	2.5	[illegible]	H.B.[a]; 23.5 (air) 13.7 (water)	external
Wind River, Wyoming	100	500 estimated	0.03-0.4	variable not given	30	H.B.[a]; size and wt. not given	external

[a] Equipment manufactured by researchers.

Sinning (1979) stated that discussions with other researchers were not very helpful in evaluating the feasibility of using radiotelemetry in waters with high conductivity. His professional contacts expressed doubt that radiotelemetry would be successful in rivers with conductivity exceeding 700 µmhos. Concern was also expressed about the propagation of radio waves in deep water. Although the researchers thought it might be possible to track fish using radiotelemetry, none of them believed that success could be guaranteed in the Green River. Sinning (1979:22) concluded "...it is apparent that feasibility of squawfish tracking in the Green River is not predictable with the present state of knowledge...".

PRIOR RESEARCH IN THE GREEN RIVER

Although there have been attempts to use ultrasonic telemetry in the Green River (McAda and Wydoski 1980), the only known attempt to use radiotelemetry was by Holden and Shelby (1978). These authors surgically implanted radio transmitters in seven Colorado squawfish. They were able to locate only one fish, which was lost after 1.5 months. They stated that the main reason for their lack of success was failure of the transmitters, causing (p. viii): " ...weakening of signal strength over time, changes in frequency, and weakness in initial strength."

Sinning (1979) evaluated Holden and Shelby's (1978) work and believed that some of the problems encountered in the study were caused by use of antennaless and long life (therefore low power) transmitters. Sinning (1979) predicted a loss in radiated power of two-fold due to the long life specification and a loss of five-fold from the antennaless design. He adds that (p. 23): "... the transmitters used by Holden and Shelby likely produced no more than 10 percent of the output that commercial transmitters would have produced."

Holden and Shelby (1978) did not report water conductivity values. However, with the generally high (400 to 1000+ µmho) conductivities in the Green River, it is obvious that the transmitters used in the study were unsuitable, particularly during periods when conductivities exceeded 600 µmhos.

The problem of frequency drift that Holden and Shelby(1978) encountered may have been related to transmitter design, because antennaless designs can cause frequency variations. Sinning (1979) concluded (p. 24): "... it is possible that some or all of the frequency drift observed ... was a result of the antennaless design..."

It is unclear why all but one fish was lost immediately after release in Holden and Shelby's study (1978). Based on the response of the one fish, it apparently exhibited abnormal behavior. This behavior could have been caused by the transmitter being too large for the fish or because the fish may not have been held long enough before release for the incision to heal. A continuous stitch was used instead of a series of discrete sutures. Failure of one of the two knots could have caused a rupture of the sutured wound and death of the fish. Problems with transmitter size and transmission could have contributed to the loss of other fish.

Although Holden and Shelby (1978) encountered problems in their study, their limited success in using radiotelemetry in the Green River prompted future investigations.

U.S. FISH AND WILDLIFE SERVICE FIELD STUDIES

Introduction

In March 1980, the U.S. Fish and Wildlife Service initiated a radiotelemetry study of endangered fishes in the Green River in conjunction with the Colorado River Fisheries Project (Miller et al. 1981). Field operations for the radiotelemetry study were directed from the FWS Field Station in Vernal, Utah. More detailed information about this study is available in Tyus et al. (1981).

It was evident from both a theoretical (Sinning 1979) and practical standpoint (McAda and Wydoski 1980) that ultrasonic telemetry would not be effective in monitoring movements of fishes in the Green River. However, the limited success with radiotelemetry reported by Holden and Shelby (1978) indicated that this technique might be effective.

Emphasis in this report is on radio reception from surgically implanted transmitters in fishes in the natural environment, although some standardized data obtained by immersing "naked" transmitters are reported. The study area included the Green River from Jensen, Utah, to its confluence with the Colorado River, over 482.7 km downstream. Within the area, the river flows through a long stretch of whitewater in Desolation and Gray Canyons, has a relatively high conductivity (ranging from about 200 to 1600 µmho in 1980), and is full of underwater objects and obstructions. The river, however, is quite shallow through most of the study area, a factor that is important for success with radiotelemetry.

Methods

FWS Colorado River Fishery Project personnel began testing radiotelemetry equipment in the Green River in March, 1980. Field testing was done with AVM and Smith-Root radio transmitters (fish modules) operating in the 40.660 to 40.700 MHz and 30.0 to 30.300 MHz range. The radio receivers were Smith-Root search (SR-40) and standard tracking (RF-40) types. Larsen Kulrod NMO-40 whip antennas and Smith-Root loop antennas were used. The field season ended in September 1980 but limited testing was done as late as December to obtain information on equipment performance in colder water (5° C).

After the project was initiated, only AVM fish modules (SM-1 type) were used for transmission. Transmission range was 40.660 to 40.700 MHz. The module was powered by a mercury (Hg-630) battery and rated at a theoretical life of 215 days, derived by dividing the battery capacity (14 milliamp-days) by the expected current drain (0.064 milliamps). The module weighed only about 11 grams. Transmissions from the fish modules were pulsed at different rates from about 60 to 90 counts per minute.

Radio transmitters were surgically implanted in the fish immediately after capture. The fish were held in a 2.5 x 4 m holding pen (Fig. 3) in the Green River for one to two weeks after surgery . The surgical procedure was similar to Bidgood (1980) except that the incision was made on the lateral aspect of the body wall, immediately anterior and dorsal to the insertion of the right pelvic fin (Fig. 4), separate sutures were used, and knots were coated with "Krazy glue".

Fish were located with the whip antenna mounted on a 20 cm^2 piece of 0.5 cm thick flat steel plate, elevated about 4 m above the water surface on a 4 cm^2 wooden post. All initial locating was done by boat or aircraft. Loop antennas were used to triangulate fish positions at close range by boat and from shore.

Aircraft were used throughout the study to locate fish. A Piper Supercub, operated by the U.S. Fish and Wildlife Service, Division of Animal Damage Control, provided the best results because it could fly slowly at a low altitude (100 km/h speed at 105 m altitude). The use of another airplane, flying at about 150 kph, provided poor results. Two nmo-40 whip antennas were attached to wing struts on the airplane and two receivers (a search and pinpoint type) were used with headphones.

Water conductivities (µmho/cm) were measured with a Yellow Springs Model 33 Meter (not temperature compensated). Two meters were often tested together to make sure they were operating correctly. Temperature readings from the conductivity meter were verified by a handheld thermometer. Following the American Public Health Association's (1971) Standard Methods text, conductivity readings were converted to the standard equivalent value at 25° C.

Six Colorado squawfish (TL 508 to 707 mm) and one razorback sucker (TL 510 mm) were captured in April and May, surgically implanted with AVM fish modules (SM-1) (Figs. 5 and 6), and released. These fish were tracked by different methods until September, the conclusion of the 1980 study.

On December 18, 1980, two AVM transmitters (SM-1), one having a mercury and one a lithium battery, and one Smith-Root small fish module were tested in the study area at different depths. All transmitters pulsed the signal at about 60 counts-per-minute. Water conductivity was 480 µmho (770 µmho corrected to 25° C) and water temperatue was 5° C. All transmitters worked satisfactorily. One transmitter (AVM No. 17010), which had earlier been retrieved from Colorado squawfish No. 001, had been refrigerated. Receiving antennas were about 4 m above the water surface.

Figure 3. River holding pen, Green River, Utah.

Figure 4. Initial incision of anesthetized Colorado squawfish.

Figure 5. Insertion of AVM fish module into anesthetized Colorado squawfish.

Figure 6. Suturing Colorado squawfish with surgically implanted radio transmitter.

Results and Discussion

The equipment functioned satisfactorily in March. At this time, water conductivities were about 500 µmho, and it was not difficult to locate fish (Table 4). The Larsen Kulrod whip antenna, coupled with the RF-40 receiver, allowed workers to easily identify signals up to 200 m away from a fish. The less effective loop antenna had a range of approximately 50 m. The Smith-Root search receiver was ineffective and had to be returned to the manufacturer for a tuning adjustment; after tuning, it performed satisfactorily.

On the day of its release (April 15), Fish No. 001 was monitored with the Smith-Root RF-40 receiver and whip antenna while it was in the river holding pen. The fish could be detected across the river, a distance of 150 m. The maximum water depth in the pen was 1.5 m and water conductivity was 812 µmho. This conductivity severely limited the range of both antennas. The range of the loop antenna was decreased from 50 m in March (conductivity of about 500 µmho) to about 30 m in April (conductivity of about 800 µmho). In addition to the increasing conductivity affecting detection, another phenomenon was noted. The received radio signal would alternately become stronger and weaker and, occasionally, the signal could not be detected. Apparently this response was attributed to movements of the fish in the pen which changed the position of the transmitting antennas.

Fish No. 001 was released at the mouth of a small backwater (the initial capture point) and its movements were monitored for approximately eight hours. The fish moved into midstream and usually remained near a shallow (0.5 m) sand bar. Radio reception was good enough to locate the fish across the river (about 100 m) with the elevated whip antenna, but not with the loop antenna. After location, the fish was approached by boat and its position pinpointed with the loop antenna. Water depths in this portion of the river were less than 1.5 m and conductivity was 810 µmho. The river was broad, with many sandy bars and shoals, especially in midchannel.

On the morning of April 16, the fish moved downstream and contact was maintained with the elevated whip antenna. River depth had increased in some reaches to a midchannel depth of about 2 m. The maximum range from the boat to the fish using the elevated whip antenna was about 150 m during the day (water conductivity 780 µmho). It was difficult to obtain a good signal at the end of the day. This was apparently caused by the fish moving into a shallow backwater next to a relatively steep dropoff which probably blocked the signal.

Early on April 17, fish No. 001 was relocated with the elevated whip antenna at an approximate distance of 175 m in a shallow side channel. When located, the boat was in the main channel opposite the mouth of the side channel. The exact position of the fish (0.5 m deep) was located by using the loop antenna on foot. At times, the fish was visible, and the loop antenna could detect the signal to a distance of approximately 50 m.

During the afternoon, the fish moved down the side channel into an area about 3 m deep. There were momentary losses of contact even with the elevated

Table 4. Water conductivity (μmho/cm)[a], Green River, Utah 1980. Temperature rounded to degrees Centigrade[b].

Month	n	Conductivity range	Conductivity $\bar{x}$	Temperature $\bar{x}$	Standard[a] conductivity
April	27	420- 770	443	9	620
May	13	245- 625	334	15	401
June	11	175- 291	223	19	252
July	9	240- 291	433	18	519
August	7	750-1200	895	25	895
September	6	610- 950	809	21	890

[a] Corrected to 25° C.

[b] Readings taken in the Green River immediately below the Duchesne River are omitted due to the very high conductivity in the Duchesne River.

whip antenna. Each time contact was re-established, and the fish remained in the same spot. When the boat was anchored at this spot, the loop antenna was virtually useless.

The fish surfaced at times, and reception became very strong, almost "deafening." Reception at other times was very weak. Apparently, the fish ascended and descended in the water column, and a 3 m depth was the limit of radio reception at the estimated conductivity of 800 to 1000 µmho.

On April 21, rising water flooded the holding pen, and three implanted fish escaped. One of these fish was located in midchannel not far from the holding pen. On April 22, this fish (No. 165) was relocated in the same general area in water 1.3 m deep. The signal was adequate for the whip antenna from a distance of about 80 m. Conductivity was about 940 µmho.

On April 24, fish No. 028 was located about 3 m from the bank, when the conductivity was 700 µmho. The reception was identical to that experienced with fish No. 001 on April 15 at a conductivity of 812 µmho. Radio reception with the elevated whip was adequate to over 100 m, while the loop antenna was useful only at distances less than 50 m and usually between 25 to 30 m.

Figure 7, illustrating receving antenna efficiency, was drawn from results obtained using crude experimental techniques with "naked" transmitters. It displays general relationships between water depths and the distance an antenna can detect signals. At 2 m deep, the most effective antenna was the whip antenna with a ground reference plane. The whip antenna without a base was less effective, but still more effective than the loop antenna. The loop antenna was useless at distances beyond 60 m.

The three transmitters performed similarly, although the small AVM fish module seemed to produce a slightly better signal. This could have been a function of transmitted power or due to auditory quality perceived by the radio receiver. This type of performance was unexpected because the module had been retrieved from an implanted fish after being in operation for more than four months. Some fish modules produced a "better sound" than others, depending to some extent on the relative length of the pulsed transmission. However, some tones were "mushy" and some "sharp". Sharp bursts of sound are more desirable for radio reception.

Ranges of transmitters can be increased by implanting transmitters in fish. According to Ringe (pers. comm.), results with Smith-Root antennas anchored in the mouth of salmon give a significant increase in apparent signal strength over "naked" transmitters. However, we did not experience more than a minor increase in range when transmitters were implanted.

Conclusions

Results of this study indicate that it is possible to use radiotelemetry to follow movements of fish, even in rivers where conductivities are relatively high. Field sampling produced better results than expected, mainly because of shallow water and the behavior of the fishes.

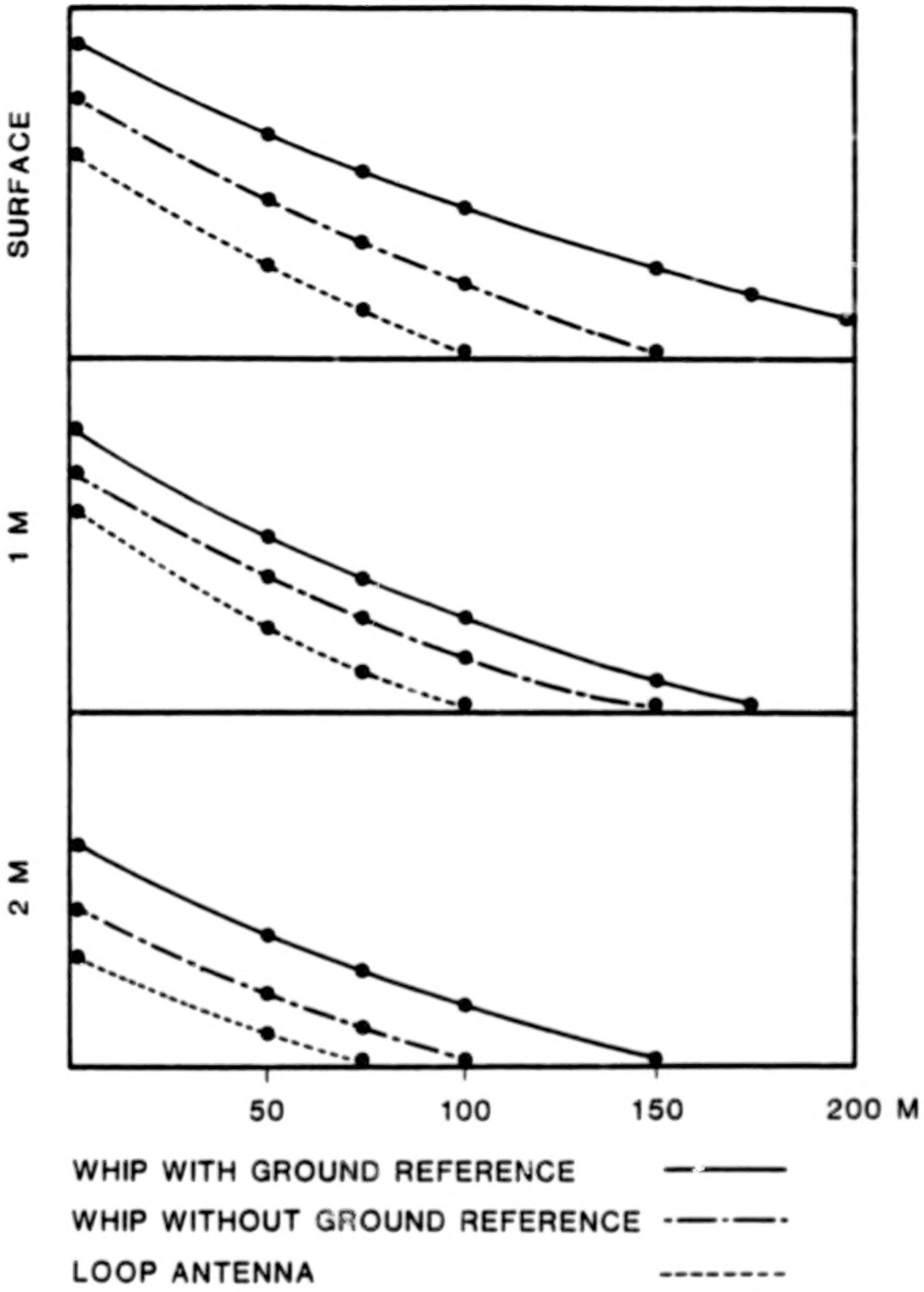

Figure 7. Relationships between relative signal reception strengths for three antenna arrangements and received signal distances for transmitters positioned at the surface, 1m, and 2m below the surface.

Sinning (1979) assumed that the water in the Green River was deeper than the water in our study area. Very little of the Green River in our study area was over 2 m deep, although depths of 3 m were encountered. Radiotelemetry was more difficult to use in other stretches of river, especially canyon areas. Fish were located by airplane in Desolation and Labyrinthe Canyons where tracking was not attempted by boat. Our findings that range decreased with increasing depth and conductivity were similar to results obtained by Knight (pers. comm.). Knight has received signals from implanted fish in water with substantially higher conductivities than those in our study area, but only where the water was very shallow.

The released fish (other than No. 001, which was obviously stressed) tended to remain in the general area of their release, or to return where captured and remain there for weeks. This behavior made them easy to find and study. Also, the fish tended to occupy the shallow areas next to dropoffs, thereby enhancing our ability to locate them. Field workers who plan to use radiotelemetry should carefully consider all factors including equipment limitations; and physiochemical characteristics of water before decisions are made to initiate studies.

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Theoretical and applied information about radiotelemetry related to rivers with high conductivity is presented in this report. Theoretical information is presented in a simplified form for investigators new to the radiotelemetry field. Radiotelemetry and ultrasonics are compared as methods for obtaining information about fish movements in turbulent, turbid river systems. Results from field studies were used to evaluate the reception of radio transmissions from fish under natural conditions.

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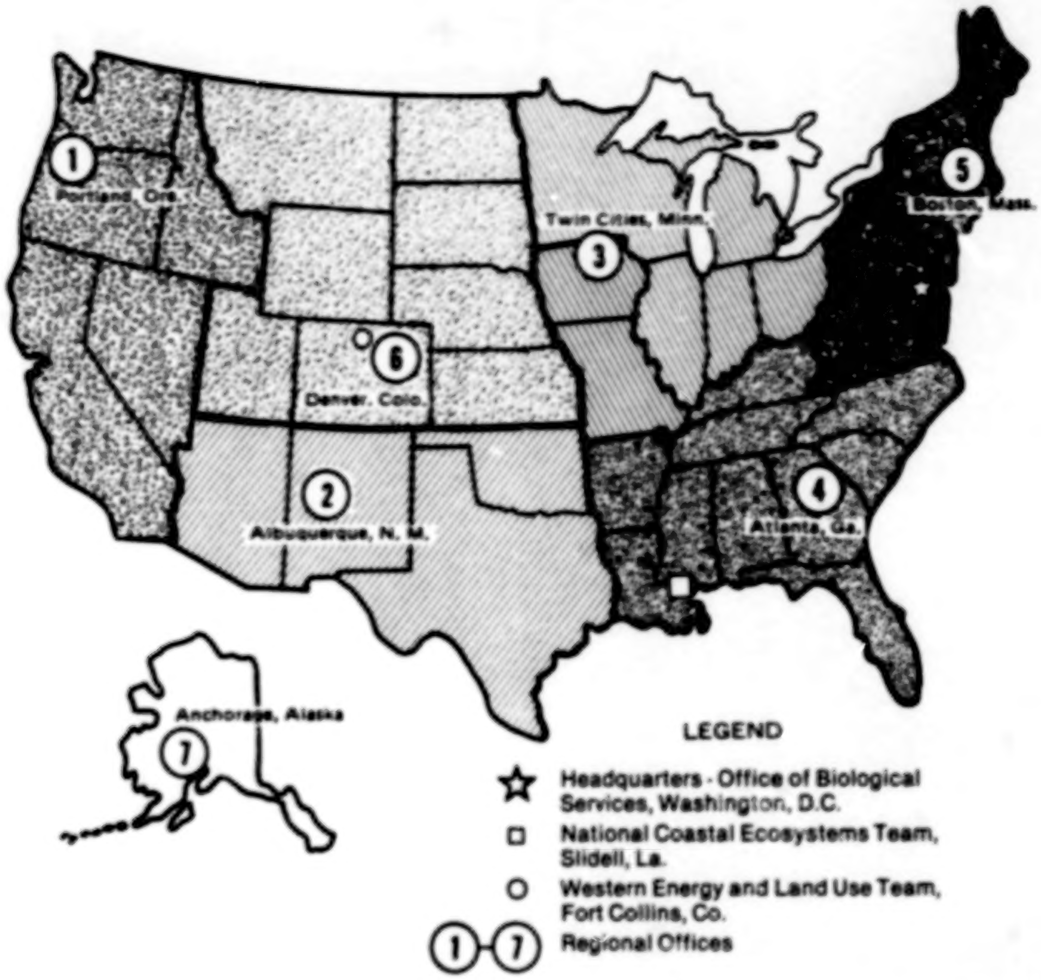
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